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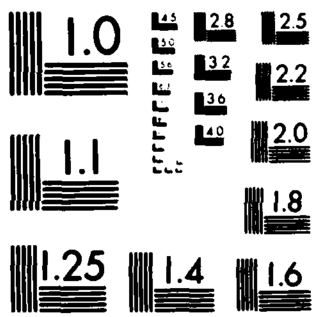

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20. ABSTRACT

This document is the final report for the Office of Naval Research grant number N00014-79-C-0624, entitled "Parametric Acoustic Array Formation via Weak Collinear and Noncollinear Interaction in Dispersive Fluids." This final report contains a historical review of the technical and administrative highlights of the research project. The details of the scientific findings are available in a separate technical memorandum of the same title, available through the Defense Technical Information Center. Briefly, the project was a theoretical investigation of the effects of dispersion on the nonlinear formation of a difference-frequency beam from two primary beams. The approach involved both analytical and numerical solutions to the nonlinear and dispersive paraxial wave equation with emphasis on Gaussian beam solutions. In the case of collinear primary beams, known results were reproduced, but with some significant errors corrected. Noncollinear interaction of finite width beams was investigated for the first time in this project. Some unexpected results were discovered in this case: it was found that the finite beam width caused the difference beam to have a directivity maximum near the axis of the primaries, rather than in the direction of the primary wave-vector difference, and decreased the conversion efficiency to significantly below the plane-wave efficiency. Further research in this area is indicated.

ONR FINAL REPORT
N00014-79-C-0624
1 August 1979 - 30 September 1983

Parametric Acoustic Array Formation via Weak Collinear and Noncollinear Interaction in Dispersive Fluids: Final Report

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This final report presents a historical review of the technical and administrative highlights of the research program undertaken under ONR Grant N00014-79-C-0624. Details of the scientific findings can be found in the technical report "Parametric Acoustic Array Formation via Weak Collinear and Noncollinear Interaction in Dispersive Fluids," written by Mark F. Hamilton who was the graduate student supported by the grant. This technical report may be referenced through the Defense Technical Information Center Report No. ADA 130533, or through the Applied Research Laboratories, University of Texas, Austin, Report No. ARL-TR-83-19.

The original idea for this research was formulated by Francis H. Fenlon, Associate Professor of Engineering and Senior Research Associate of the Applied Research Laboratory at The Pennsylvania State University. Briefly, the idea was to study the effects of induced and inherent dispersion on the conversion-efficiency of an acoustic parametric array. In a parametric array, two primary sound fields with frequencies ω_1 and ω_2 and wave vectors $\vec{k}_1$ and $\vec{k}_2$ interact in a nonlinear medium to produce secondary fields at sum and difference frequencies. If the medium is nondispersive (the speed of sound c is independent of frequency) then the nonlinear conversion is most efficient for collinear plane waves, since in this case the phase of the secondary wave matches the beating of the primary waves [i.e., $k_\pm \equiv (\omega_1 \pm \omega_2)/c = k_1 \pm k_2$]. However if the medium is dispersive, then maximum efficiency occurs when the primary and secondary waves intersect at a particular angle, and only one type of secondary wave [sum or difference frequency] is efficiently generated depending on whether the dispersion is positive [c increases with frequency] or negative [c decreases with frequency]. In sonar applications the difference frequency wave is of greater importance, and the use of dispersion to enhance its generation is of practical interest.

Also of practical interest is the effect of the finite size of the projector which generates the primary beams; the finite projector size gives the primary waves an extended angular spectrum (referred to as beam-spreading or diffraction) so that their interaction is intrinsically noncollinear and so that the finite wave amplitude decreases from geometrical spreading as well as from thermoviscous absorption in the fluid. The original proposal considered the effects on seconary beam generation from two sources of dispersion: artifical, boundary-induced dispersion, and inherent dispersion arising from relaxation mechanisms. During the course of the research, emphasis shifted solely toward the latter source of dispersion. Although there exist papers dealing with the effect of dispersion on infinite plane waves, the results in Mr. Hamilton's report are the first to describe dispersion effects with finite beams. His results uncover some unexpected behavior and indicate that further research should be undertaken; his work also reveals many errors in the existing literature. These results will be discussed briefly in this report.

Mr. Hamilton began working on this project under the guidance of Professor Fenlon in 1980, and after a year he mastered the relevant concepts existing in the literature and began working on new calculations. Initial results were reported at the Ottawa, Canada meeting of the Acoustical Society of America [J. Acoust. Soc. Am. 69, S81 (1981)] in May 1981. In June 1981 the theoretical acoustics community suffered considerable loss when Professor Fenlon passed away. Through his diligence and excellence as a teacher, he had advanced the project to a point where Mr. Hamilton could see it to completion. Mr. Hamilton had become sufficiently versed in the field that he was able to substitute for Professor Fenlon in delivering the basic nonlinear acoustics lectures at the Penn State Underwater Sound School in October 1981 and again in 1982.

In order to allow the research project and its ONR funding to continue, Physics Professor Julian D. Maynard, a friend and colleague of Professor Fenlon, assumed the responsibilities of principal investigator and advisor for Mr. Hamilton's academic affairs. The transfer of the grant to Professor Maynard was officially approved in November, 1981 as a modification A00002 of the original proposal. For the advanced scientific guidance of the nonlinear acoustics research, aid was most generously offered by Professor David J. Blackstock of the University of Texas. In addition to being distinguished in the fields of physical and nonlinear acoustics, Professor Blackstock was a personal friend of Professor Fenlon. In order for the scientific advising to be administered conveniently, it was necessary that Mr. Hamilton complete his theses work at the University of Texas; his degree would still be conferred through the Acoustic Program at Penn State. To qualify as an off-campus degree candidate, Mr. Hamilton was required to complete his Ph.D. candidacy exam. In November 1981 he passed this exam with an above-average score, after which his Ph.D. degree committee, with Professor Blackstock established as an external member, was formed. After completing these academic requirements, Mr. Hamilton moved to Texas. Reimbursement for this move, costing approximately $1000, was approved and paid through the ONR grant.

Because of the delays in the progress of the research caused by the change in theses advisor, the move to Texas, etc., it was agreed that a non-cost extension of the grant would be necessary to complete the project. A new termination date of May 31, 1983 (giving Mr. Hamilton an additional ten months to compete his Ph.D. thesis) was requested and approved in March 1982. A revised budget including Mr. Hamilton's travel expenses to the University of Texas and his various research expenses there, was also approved at this time.

In order to conveniently monitor Mr. Hamilton's progress, it was agree that the bi-annual conventions of the Acoustical Society of America would be used as meeting places for Mr. Hamilton and Professor Blackstock from Texas and Professor Maynard from Penn State. Such meetings took place at the April 1982 convention in Chicago and the November 1982 convention in Orlando, Florida. At the Orlando meeting, Mr. Hamilton delivered a talk [J. Acoust. Soc. Am. 72, S41 (1982)] in which he presented three-dimensional plots of the sound field resulting from two collinear, interacting Gaussian beams. These clearly showed that a sufficient amount of dispersion caused the maximum radiation to be shifted off axis, at an angle θ given by $k_1 - k_2 = k_- \cos\theta$. An important aspect of this work was the correction of numerous errors existing in the literature.

While at the University of Texas, Mr. Hamilton completed the analytical and numerical investigation of the collinear interaction, and then extended the calculations to the case of noncolliner interaction. The culmination of this work was Mr. Hamilton's thesis (which is reproduced in the technical memorandum mentioned in the introduction of this report) a shortened version of the thesis submitted for publication to the Journal of the Acoustical Society of America (pending), and a paper prsented at the Eleventh International Congress on Acoustics in Paris. An excellent summary of the scientific accomplishments of this project, including principal techniques and results, is contained in Appendix A, which is a reproduction of the paper prepared by Mr. Hamilton for the Paris meeting. A significant result was the effect of the finite beam size in the noncollinear beam interaction. When the beams intersect at the resonance angle, the position of maximum radiation was not in the direction of $\vec{k}_1 - \vec{k}_2$, but remained close to the primary beam axes. This was a result of the directionality of the finite width interaction region. Another interesting

result was the limited secondary field generation caused by the reduced interaction length of the intersecting, finite width primaries. Further investigation of this compromise in the noncolliner, finite beam situation is indicated.

In order to complete the technical memorandum and final report covering the project and to include the Paris conference as part of the project, it was necessary to request a second no-cost extension of the grant. A termination date of September 30, 1983 was approved in May 1983.

On April 8, 1983, Mr. Hamilton passed his comprehensive examination with above average scores, and on the following day he successfully defended his thesis, thus completing the requirements for the Ph.D. degree.

PARAMETRIC ACOUSTIC ARRAY FORMED BY NONCOLLINEAR PRIMARY BEAMS IN A DISPERSIVE FLUID

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Introduction. The effect of dispersion on parametric acoustic arrays formed by collinear interaction of weak finite amplitude waves is well understood.[1] Inherent dispersion in fluids results, for example, from relaxation phenomena, or inhomogeneities such as bubbles. Compensation for the detrimental effects of dispersion on the nonlinear interaction of two finite amplitude plane waves is achieved when the two waves intersect at a suitable angle.[2] Such an approach was applied by Kozyaev and Naugol'nykh[3] in their analysis of parametric arrays formed by collimated plane primary waves in bubbly water. In this paper we extend our previous analytical work,[1] where we used Gaussian primary beams to account for dissipation and diffraction as well as dispersion, to the case of noncollinear interaction.

Theory. We begin by modifying Kuznetsov's[4] nonlinear paraxial wave equation to account for dispersion. In the frequency domain our modified equation assumes the parabolic form

$$\partial_z p_\omega + [\alpha'_\omega + (ic_o/2\omega)(\partial_x^2 + \partial_y^2)]p_\omega = (i\beta\omega/2\rho_o c_o^3)p_\omega * p_\omega \quad , \tag{1}$$

where $p_\omega(x,y,z)$ is the acoustic pressure spectral amplitude of a quasi-plane wave traveling in the positive z direction, $p_\omega * p_\omega$ represents convolution in the frequency domain, ρ_o is the ambient density of the fluid, c_o is a reference sound speed, and β is the coefficient of nonlinearity (e.g., $\beta = (\gamma+1)/2$ for gases, where γ is the specific heat ratio). Dispersion is taken into account via the imaginary part of $\alpha'_\omega = \alpha_\omega + i(k_\omega - \omega/c_o)$, where α_ω is the attenuation coefficient, and $k_\omega = \omega/c_\omega$ is the wavenumber, where c_ω is the sound speed at angular frequency ω. See Ref. 5 for a similar treatment of the Burgers equation.

By restricting our analysis to weakly nonlinear interactions, we can solve Eq. (1) via successive approximations (see Ref. 6, Appendix A). First we seek the solution for a primary beam whose direction of propagation forms an angle ϕ with the z axis in the x-z plane. For a Gaussian beam the boundary condition becomes

$$p_j(x,y,0) = p_{Gj} \exp\{-(x^2 + y^2)/\varepsilon_o^2 - i\omega_j\phi_j x/c_o\} \quad , \tag{2}$$

where $j = 1,2$ represents ω_1 and ω_2, p_G is the peak source amplitude, and ε_o determines the spot size of the beam. In the first approximation, where we neglect $p_\omega * p_\omega$, the solution for the primary beams is thus found from Eq. (1) to be

$$p_j(X,Y,Z) = p_{Gj}\,\frac{e^{-a_j'Z}}{1 - iZ/\Omega_j}\,\exp\left\{-\,\frac{X^2 + i2\Omega_j D\phi_j X + Y^2 - i\Omega_j D^2 Z\phi_j^2}{1 - iZ/\Omega_j}\right\}\,, \qquad (3)$$

where we have introduced the dimensionless coordinates $X = x/\varepsilon_o$, $Y = y/\varepsilon_o$, and $Z = z/z_o$, where $z_o = \omega_o\varepsilon_o^2/2c_o$ is the mean collimation distance of the primaries, and $\omega_o = (\omega_1 + \omega_2)/2$ is the mean primary frequency. We also let $\Omega_j = \omega_j/\omega_o$, $a_j' = \alpha_j z_o$, and $D = \omega_o\varepsilon_o/2c_o$. In the farfield paraxial region ($Z >> 1$) we can let $X = DZ\theta_x$ and $Y = DZ\theta_y$, where θ_x and θ_y are azimuthal angles in the x-z and y-z planes, respectively, whereby the directivity function for the primaries is found from Eq. (3) to be $\exp\{-\Omega_j^2 D^2[(\theta_x - \phi_j)^2 + \theta_y^2]\}$.

To obtain a first approximation of the solution for the difference frequency signal ($\omega_- = \omega_1 - \omega_2$), we solve Eq. (1) after replacing $p_\omega * p_\omega$ by $p_1 p_2^*$, where p_2^* is the complex conjugate of p_2. Without loss of generality we let $\phi_2 = 0$ and $\phi = \phi_1$, which creates the geometry depicted in Fig. 1. Solving Eq. (1) for p_- we thus obtain

$$p_-(X,Y,Z) = i\Omega_1\Omega_2\Omega_- D^2 P_o e^{-a_-'Z}\int_0^Z \exp\left\{\frac{i\Omega_1^2 D^2\phi^2\eta}{\Omega_1 - i\eta} - \frac{\Omega_1^4 D^2\phi^2(\Omega_2 + i\eta)}{(\Omega_1 - i\eta)(2\Omega_1\Omega_2 + i\Omega_-\eta)}\right.$$
$$\left. - \frac{2\Omega_1\Omega_2 + i\Omega_-\eta}{A + B\eta}\left[\left(X + \frac{i\Omega_1^2 D\phi(\Omega_2 + i\eta)}{2\Omega_1\Omega_2 + i\Omega_-\eta}\right)^2 + Y^2\right] - a_T'\eta\right\}\frac{d\eta}{A + B\eta}\,, \qquad (4)$$

where $A = \Omega_1\Omega_2(1 - i2Z/\Omega_-)$, $B = Z + i(\Omega_- + 2\Omega_1\Omega_2/\Omega_-)$, $\Omega_- = \omega_-/\omega_o$, $P_o = \beta p_{G1}p_{G2}/\rho_o c_o^2$, and $a_T' = a_T - i2\delta\Omega_- D^2$, where $a_T = (\alpha_1 + \alpha_2 - \alpha_-)z_o$. The dispersion coefficient is $\delta = 1 - |\vec{k}_1 - \vec{k}_2|/k_-$, which for collinear interaction (i.e., $\phi = 0$) reduces to $\delta_o = 1 - (k_1 - k_2)/k_-$, where δ_o is a measure of the inherent dispersivity of the fluid. We obtain $\delta_o = 0$ for no dispersion, $\delta_o > 0$ for normal dispersion ($c_1 \geq c_2 > c_-$), and $\delta_o < 0$ for anomalous dispersion ($c_1 \leq c_2 < c_-$).

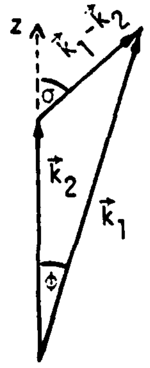
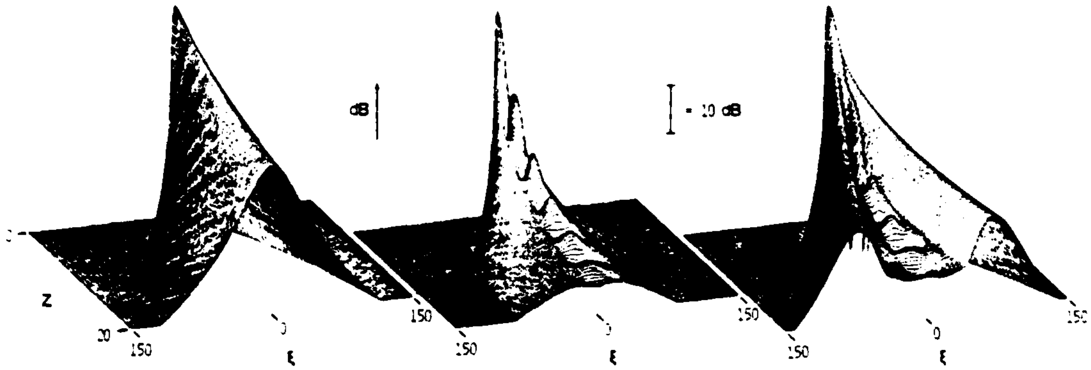


FIGURE 1

<u>Results</u>. We first use Eq. (4) to calculate the difference frequency field for collinear interaction with $\delta_o = 0$, -0.01, and 0.01. The field plots are presented in Fig. 2, where we have chosen $\Omega_- = 0.1$ (note that $\Omega_1 = 1 + \Omega_-/2$ and $\Omega_2 = 1 - \Omega_-/2$), $a_T = 0.1$, $a_- = 0$, and $D = 30$. Since the field is axisymmetric for $\phi = 0$, we let $\xi^2 = X^2 + Y^2$. When there is no dispersion, as depicted in Fig. 2(a), the virtual sources interact synchronously with the difference frequency signal, giving rise to the end-fire radiation pattern. As seen from Figs. 2(b) and 2(c), dispersion causes asynchronous interaction, with the interaction region being clearly defined by the resulting spatial oscillations. For normal dispersion ($\delta_o > 0$), the



(a) $\delta_o = 0$ (b) $\delta_o = -0.01$ (c) $\delta_o = 0.01$

FIGURE 2 - Pressure fields where $\phi = 0$, $\Omega_- = 0.1$, $a_T = 0.1$, $a_- = 0$, $D = 30$

phasing of the virtual sources corresponds to a speed which is greater than c_-, while for anomalous dispersion ($\delta_o < 0$), the opposite is true. Radiation from the interaction region is thus analogous to that from bending waves on an infinite plate. When $\delta_o > 0$, the direction of maximum radiation is shifted off axis to an angle which approaches $\cos^{-1}[(k_1 - k_2)/k_-]$ for collimated plane wave interaction. When $\delta_o < 0$, the radiation is of an evanescent nature and the maximum remains on axis.

Only for $\delta_o > 0$ can phase matching in the interaction region be attained via intersection of the primaries. Phase matching is achieved by increasing the angle of intersection, ϕ, until the wavenumber of the virtual source distribution, $|\vec{k}_1 - \vec{k}_2|$, equals k_-. We will investigate the effect of noncollinear interaction by way of the farfield radiation pattern of the difference frequency signal. The farfield asymptotic form of Eq. (4) is extremely complicated and will not be presented here. However, tremendous simplification results for an array where attenuation restricts nonlinear interaction to the nearfield of the primaries. Thus, for large a_T and small Ω_-, the farfield asymptotic form of Eq. (4) reduces to

$$p_- = -\frac{\Omega_-^2 D^2 P_o}{2a_T}\,\frac{e^{-a_-' Z}}{Z}\,\frac{\exp\{-(\Omega_-^2 D^2/2)[(\theta_x - (\Omega_1/\Omega_-)\phi)^2 + \theta_y^2]\}}{1 + i(\Omega_- D^2/a_T)(\theta_x^2 - \phi\theta_x + \theta_y^2 - 2\delta)}\, e^{-i\Omega_- D^2 Z\theta^2}, \quad (5)$$

where $p_- = p_-(\theta_x, \theta_y, Z)$ and $\theta^2 = \theta_x^2 + \theta_y^2$. When $\phi = 0$ and $\delta_o = 0$, the denominator of the directivity function in Eq. (5) reduces to Westervelt's[7] result for an absorption-limited array.

To calculate farfield radiation patterns for various values of ϕ, we evaluate Eq. (4) with $Z = \infty$, using the same parameters as in Fig. 2(c). In addition, it is assumed that both primaries propagate at the same speed. The angle ϕ_o for which $\delta = 0$ thus becomes 0.82°. In Fig. 3 are presented

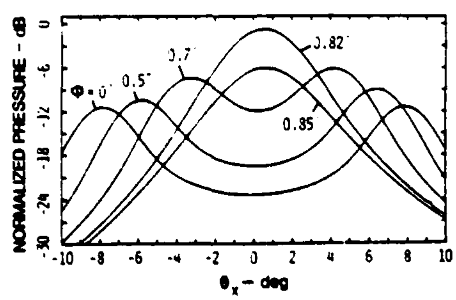
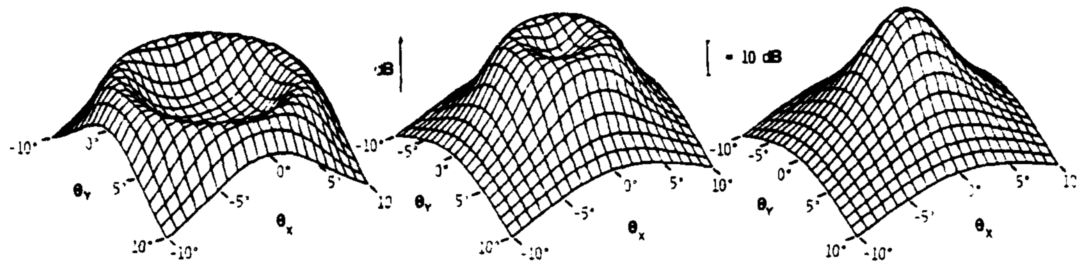


FIGURE 3 - Farfield directivity $\theta_y = 0$



(a) $\phi = 0°$ (b) $\phi = 0.7°$ (c) $\phi = 0.82°$

FIGURE 4 - Farfield radiation patterns

the farfield radiation patterns for the x-z plane (i.e., where $\theta_y = 0$). Likewise, complete radiation patterns are shown in Fig. 4.

From Figs. 2(c), 3, and 4(a), we find that collinear interaction with $\delta_o > 0$ produces a dip in the center of the radiation pattern. As ϕ approaches ϕ_o, the dip disappears, and the field resembles that depicted in Fig. 2(a). Increasing ϕ beyond ϕ_o causes geometric dispersion to overcompensate for the inherent dispersivity of the fluid. The net result of such overcompensation is a field resembling that depicted in Fig. 2(b), since we then have $\delta < 0$. As seen in Fig. 3, after the dip in the radiation pattern disappears when $\phi = \phi_o$, the farfield level is reduced for any additional increase in ϕ.

In Eq. (5), it is the denominator of the directivity function which accounts for the effect of variations in ϕ on the dip in the radiation pattern. As a_T is increased, the angular dependence of the denominator is reduced, making the aperture factor in the numerator more significant. The aperture factor attains its maximum value of unity when $\theta_y = 0$ and $\theta_x = (\omega_1/\omega_-)\phi \simeq \sigma$, where σ is the direction of $\vec{k}_1 - \vec{k}_2$ (see Fig. 1). Thus, for sufficiently high attenuation of the primaries, Eq. (5) yields results which are consistent with those for dispersive plane wave interaction.[2]

From Figs. 3 and 4, we find that the radiation pattern is not shifted significantly with respect to the z axis when $\phi \neq 0$. For example, when $\phi = \phi_o$, the peak is shifted less than one degree off axis, whereas $\sigma = 8.5°$. This is because we assumed low attenuation ($a_T = 0.1$) to emphasize the effects of dispersion. Such low attenuation permits the interaction region to extend beyond the nearfield of the primaries, whereby conditions do not approximate those of plane wave interaction.

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